PREDICTION OF CHLORIDE PROFILE AT CRACK LOCATION IN REINFORCED CONCRETE UNDER FLEXURAL LOADING

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Abstract

The chloride penetration into concrete is one of the most popular topics and very exciting in the field of concrete durability. The chloride ion acts as a main factor in causing the corrosion of the reinforcement in concrete structure. Moreover, chloride transport mechanisms in concrete are very complicated. Specifically, the cracks were recognized as one of the primary reasons causing an increase in the corrosion rate of reinforcements due to chloride attack. The aim of this research is to propose models for predicting the chloride profile at crack locations of reinforced concrete. In the present paper, the tapered crack (V-shaped crack) was introduced as a natural crack due to flexural loads. In addition to the crack width, the crack depth also played as a factor influencing the chloride penetration depth and chloride profile. Finally, the validity of the proposed model was verified by comparing with experimental results under the influence of crack characteristics. The research results showed that the predicted results fitted well with experimental ones when the immersion periods were larger than 4 weeks.

Keywords: Chloride penetration, Chloride profile, Cracked concrete, Crack depth, Crack width

Introduction

The durability of reinforced concrete structures in marine environment has been considered as a serious problem in concrete construction technology. The principle cause of reduction in durability of reinforced concrete is the reinforcement corrosion in the chloride-laden environments. Generally, the chloride ions are able to attack in the pore structure [1] and were recognized as a main factor for corrosion of the reinforcing steel in a marine environment [2]. Normally, the reinforcement is protected away from corrosion by a passive film. Once the chloride concentration at the surface of the reinforcement reach a threshold value, this passive film will be destroyed and the corrosion process is initiated. A prediction for chloride concentration at the reinforcement surface in concrete member is very necessary for the durability and service life design.

Furthermore, the cracks occurring on reinforced concrete due to external loads are unavoidable during the service life of concrete member. Like a fast access slot, the cracks may take chloride ions from the marine environment into the concrete structure. Up to now, many researchers have tried to take into account the influence of crack width on the chloride penetration into concrete structure [3-8]. They concluded that the crack width strongly influenced on the chloride diffusion and its coefficient was considered as a function of the crack width. In addition to the crack width, the crack depth is also a key parameter; especially, under external loading the crack characteristics will rise during all

stages in the life of a concrete structure and they can strongly influence on the chloride penetration [9]. However, studies about crack depth affecting the chloride penetration have not been clear and complete. On the other hand, the loading is also a parameter having an influence on the chloride penetration in concrete [10]. Mien [9] investigated and modeled the chloride penetration in plain concrete with invisible crack under combined actions of cyclic loading and tidal environment. Because of the embedded reinforcing steel in the concrete structure, the visible cracks such as tapered cracks often appear and stabilize or propagate under external loading.

In the field, the reinforced concrete structure is under the influence of combined factors, such as natural crack characteristics due to the external loading and marine environments. Particularly, when the crack occurs in the concrete cover, the rate of chloride ion is accelerated to diffuse into the concrete structure hence the durability, as a result, will be reduced quickly. For this reason, this research will carry out the effects of tapered crack characteristics, crack width and crack depth, on the chloride diffusion into cracked reinforced concrete structure under saturated condition. A numerical model was proposed to predict the chloride profile at tapered cracks of reinforced concrete structure and this model will become an important solution to evaluate the remaining service life of concrete structure when cracks appear.

**Development of Model**

Flexural loading is able to cause zones with cracks and uncrack on the tension surface of reinforced concrete, as shown in Figure 1. The chloride profile in crack zone is different with that in uncrack zone, furthermore it accumulates chloride concentration in crack zone more than in uncrack zone. From this reason, the steel reinforcement will be found in more damage in crack zone than in uncrack zone.

![Diagram](https://via.placeholder.com/150)

**Figure 1. Collecting chloride profile at crack and uncrack zones**

Generally, under saturated condition the chloride profile governed by the diffusion mechanism of chloride ions is calculated by Fick’s second law, as shown by the equation below:

\[
\frac{\partial C_i}{\partial t} = D_{ai} \frac{\partial^2 C_i}{\partial x^2}
\]  (1)
A solution to Equation (1) is given by the compliment to the error-function:

\[ C(x,t) = C_s \left( 1 - \text{erf} \left( \frac{x}{2\sqrt{D_a t}} \right) \right) \]  

(2)

where \( C(x,t) \) is chloride concentration at time \( t \) at depth \( x \); \( C_s \) is surface chloride content; \( \text{erf}(\cdot) \) is error function; \( x \) is distance from concrete surface; \( t \) is exposure time; and \( D_a \) is apparent chloride diffusion coefficient.

Up to now, many researches have concluded that the crack width played a role of increase in the chloride penetration into cracked concrete [3-8, 11]. However, in the real reinforced concrete under flexural load, the crack depth also affects the chloride penetration depth and chloride profile along the crack zone in addition to the crack width [12]. Consequently, to predict the chloride profile in a tapered crack of reinforced concrete, the chloride diffusion coefficient \( (D_a) \) has to be modified and developed. It will become the chloride diffusion coefficient in the crack zone of reinforced concrete, so that the influences of crack characteristics should be included as follows:

\[ D_a = f(W, L, D_{uncr}) \]  

(3)

where \( D_a \) is the chloride diffusion coefficient in crack zone, and is a function considering the dependence of chloride diffusion coefficient of uncrack zone \( (D_{uncr}) \) on the crack width \( (W) \) and crack depth \( (L) \).

The concept of chloride diffusion through the crack is illustrated in Figure 2. The chloride ions will diffuse in cracked reinforced concrete following two states. First, the chloride ions will diffuse through crack region and are governed by the chloride diffusion coefficient of crack \( (D_{cr}) \), as shown in Figure 2a. Subsequently, the chloride ions continuously diffuse in the uncrack region of concrete at the tip of crack. The chloride profile in this uncrack region must correlate to the coordinate axis at the exposed surface. That is why the chloride diffusion coefficient of this uncrack region \( (D_{un-eff}) \) must have a correlation to crack depth, as shown in Figure 2b. In other words, the crack depth will have an influence on the chloride profile or chloride diffusion coefficient of the uncrack region.

Figure 2. The concept for chloride diffusion coefficient at a crack location of reinforced concrete

With the assumption above, the chloride diffusion coefficient in cracked reinforced concrete is proposed as an average chloride diffusion coefficient \( (D_{av}) \) as follows:
\[ D_a = D_{av} = \frac{D_{cr} + D_{un-eff}}{2} \]  

(4)

where \( D_{cr} \) is calculated based on the crack width \( (W) \) by the following equation proposed by Djerbi [6]:

\[
D_{cr} (m^2/s) = \begin{cases} 
(2 \times 10^{-11})W - 4 \times 10^{-10}, & \text{when } 30 \mu m \leq W \leq 80 \mu m \\
14 \times 10^{-10}, & \text{when } w > 80 \mu m
\end{cases}
\]

(5)

However, in the research of Djerbi [6], the crack walls are transverse, separate, and parallel, but in the real structure and present research, the crack normally occurs as tapered crack (V-shaped crack) that the crack width is reduced in correlation to the crack depth. So, to apply the equation (5), the crack width is approximately calculated by the average of \( W_1 \) and \( W_2 \):

\[ W = \frac{W_1 + W_2}{2} = \frac{W_1 + 30}{2} \]

(6)

where \( W_1 \) is the crack mouth (crack width on the tension surface), \( \mu m \). \( W_2 = 30 \) (\( \mu m \)). Because of the effect of crack depth, the chloride diffusion coefficient of uncrack region, which is above the crack tip (Figure 2b), will be a function of crack depth as follows:

\[ D_{un-eff} = f (L, D_{uncr}) \]

(7)

where \( L \) (mm), crack depth, is assumed as a straight length from the crack mouth along the crack plane to where a crack width \( (W_2) \) is 30 \( \mu m \); \( D_{uncr} \) is the chloride diffusion coefficient in uncrack zone.

A relationship of the crack depth \( (L) \) to the chloride diffusion coefficient \( D_{un-eff} \) will be found by an experiment. This experiment is based on the short-term diffusion test (STDT) a basis of chloride migration test [13]. Furthermore, STDT is modified by the combination of ASTM C1202 [14] and Nordtest NT build 492 [15], as shown in Figure 3. In addition, in this test, the shape of applied voltage cell is modified to change from cylinder-shape specimen to cubic-shape specimen.

Figure 3. Set up of short-term diffusion test combined by ASTM C1202 and Nordtest NT build 492

The concept of this experiment reflects the relationship between chloride penetration depth in crack and uncrack zones in correlation to crack depth, as shown in Figure 4;
where $x_{uncr}$ is the chloride penetration depth at uncrack zone, $L$ is the crack depth, $x_{cr-eff}$ is the chloride penetration depth at crack zone (crack tip), affected by the crack depth.

Figure 4. The concept of the chloride penetration depth at crack and uncrack zones of reinforced concrete

Based on Nordtest NT build 492, the chloride diffusion coefficient is determined as follows:

$$D_{uncr} = \frac{Rt}{zFE} \frac{x_{uncr} - \alpha \sqrt{x_{uncr}}}{t}$$  \hspace{1cm} (8)

And:

$$D_{cr-eff} = \frac{Rt}{zFE} \frac{x_{cr-eff} - \alpha \sqrt{x_{cr-eff}}}{t}$$  \hspace{1cm} (9)

Where:

$$\alpha = 2 \sqrt{\frac{RT}{zFE}} \text{erf}^{-1} \left( 1 - \frac{2c_d}{c_0} \right); \hspace{0.5cm} E = \frac{U - 2}{L_t}$$

$z$: absolute value of ion valence, for chloride, $z = 1$; $F$: Faraday constant, $F = 9.648 \times 10^4$ J/(V.mol); $U$: absolute value of the applied voltage, V; $R$: gas constant, $R = 8.314$ J/(K.mol); $T$: average value of the initial and final temperatures in the anolyte solution, K; $L_t$: thickness of the specimen, m; $t$: test duration, seconds; erf$^{-1}$: inverse of error function; $c_d$: chloride concentration at which the color changes, $c_d \approx 0.07$ N for OPC concrete; $c_0$: chloride concentration in the catholyte solution, $c_0 \approx 2$ N.

**Experiment Testing**

**Preparation of Specimens**

In this study, three types of water-cement ratio (W/C) - 0.4, 0.5 and 0.6 - in mixtures were investigated. The ASTM Type I Portland cement (OPC) was used; concrete proportions in study are presented in Table 1. The sand and coarse aggregate were washed and dried prior to casting to remove any initial chloride content. For each type of concrete proportions, the beams with size of 100x100x500 mm were cast. After curing for 28 days, the single crack on the tension surface of each beam was generated by the bending moment with a three-point load; the crack depth was modified by varying the magnitude of applied load. There pre-cracked reinforced concrete beams will be used for two experimental programs:
To observe the influence of crack depth on the chloride diffusion coefficient ($D_{\text{un-eff}}$).
To validate the prediction model of chloride profile at tapered cracks of reinforced concrete.

### Table 1. Mix Proportion and Properties of Concrete

<table>
<thead>
<tr>
<th>Mix</th>
<th>W/C</th>
<th>Cement (kg)</th>
<th>Water (kg)</th>
<th>Sand (kg)</th>
<th>Coarse Agg. (kg)</th>
<th>Av. Comp. Str. (MPa)</th>
<th>Av. Slump (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>513</td>
<td>205</td>
<td>664.14</td>
<td>1,024</td>
<td>48.1</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>410</td>
<td>205</td>
<td>748.62</td>
<td>1,024</td>
<td>39.3</td>
<td>8.5</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>342</td>
<td>205</td>
<td>804.93</td>
<td>1,024</td>
<td>32.8</td>
<td>8</td>
</tr>
</tbody>
</table>

**Testing the Influence of Crack Depth on the Chloride Diffusion Coefficient**

The cubic specimens containing a single crack were sawed from the pre-cracked reinforced concrete beams. Before conducting the chloride diffusion test, the correlation of the crack depth to crack width along crack plane of the cubic specimen is measured on both crack sides of the cubic specimen by a digital microscope. The crack mouth on the tensile surface of cubic specimen was measured at 9 points of interval distance of 1 cm. The applied voltage for testing was 60 V. The duration time of testing was 10 hours. After testing STDT, the cubic specimens were split along the crack plane into two parts. The silver nitrate 0.1 M was then sprayed on the split surface of the concrete. After 15 minutes, the chloride penetration depth was measured as visible white precipitation of silver chloride at the crack tip ($x_{\text{cr-eff}}$). Figure 5 shows an experimental result of the chloride penetration depths in uncrack and crack zones.

![Figure 5](image)

(a) Chloride penetration depth in uncrack zone, $x_{\text{un}}$  
(b) Chloride penetration depth in crack zone, $x_{\text{cr-eff}}$

**Testing the Chloride Profile in Uncrack Zone and Crack Zone**

The back-to-back pair of reinforced concrete beams (Figure 6) containing a single crack were immerged into salt solution of NaCl 10%. After immersion periods of 2, 4, 6, 8, 16 weeks, these beams were kept at room temperatures for 7 days to thoroughly dry the surface. Then, a drill bit having a diameter of 1 inch was used to drill a hole on the tensile surface of reinforced concrete beam to collect the concrete powder. The samples of the concrete powder of 10 gram will be collected in an interval depth of 5 - 10 mm. To verify
the proposed model for predicting chloride profile in the crack zone, the concrete powder samples in crack zone were obtained, and were then analyzed by the conventional chemical analysis [16]. The concrete powder samples in uncrack zone were also collected to find out the apparent chloride diffusion coefficient in uncracked zone following the standard instructions [17]. The experimental results, such as the crack width, crack depth and the apparent chloride diffusion coefficient in uncrack zone, are showed in Table 2.

### Figure 6. The back-to-back pair of reinforced concrete beams immersed into salt solution

**Table 2. Experimental Results of Crack Characteristics and Chloride Diffusion Coefficient**

<table>
<thead>
<tr>
<th>Immersion Periods (week)</th>
<th>W/C</th>
<th>Crack No.</th>
<th>Crack Mouth (W&lt;sub&gt;1&lt;/sub&gt;, mm)</th>
<th>Respective Crack Depth (L, mm)</th>
<th>Apparent Chloride Diffusion Coefficient at Uncrack Zone (D&lt;sub&gt;uncr&lt;/sub&gt;, m&lt;sup&gt;2&lt;/sup&gt;/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
<td>1</td>
<td>0.058</td>
<td>32.5</td>
<td>3.77E-11</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>0.077</td>
<td>36</td>
<td>5.33E-11</td>
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<tr>
<td></td>
<td>0.6</td>
<td>1</td>
<td>0.081</td>
<td>32</td>
<td>8.87E-11</td>
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<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>0.093</td>
<td>41.5</td>
<td>3.16E-11</td>
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<tr>
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<td>0.6</td>
<td>1</td>
<td>0.083</td>
<td>41.5</td>
<td>4.74E-11</td>
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<tr>
<td></td>
<td>0.4</td>
<td>1</td>
<td>0.045</td>
<td>21.5</td>
<td>2.43E-11</td>
</tr>
<tr>
<td></td>
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<td>1</td>
<td>0.052</td>
<td>27.5</td>
<td>2.19E-11</td>
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<tr>
<td></td>
<td>0.6</td>
<td>1</td>
<td>0.072</td>
<td>33</td>
<td>2.28E-11</td>
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<tr>
<td></td>
<td>0.4</td>
<td>1</td>
<td>0.089</td>
<td>42</td>
<td>2.47E-11</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>0.074</td>
<td>31.5</td>
<td>2.43E-11</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1</td>
<td>0.080</td>
<td>40.5</td>
<td>3.25E-11</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>0.107</td>
<td>45.5</td>
<td>1.65E-11</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.101</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

**Results and discussions**

**The Influence of Crack Depth on the Chloride Diffusion Coefficient**

Figure 7 shows the experimental results of the influence of crack depth on the chloride diffusion coefficient by STDT. The results also pointed out that the values of chloride diffusion coefficient for W/C of 0.6 were higher than W/C of 0.5 and 0.4 at the same depths of cracks. At the same depths of cracked concrete, the chloride diffusion
coefficients are still governed by the effects of concrete proportions, typically, water-cement ratios. Because the chloride diffusion takes place in the crack and in the matrix of concrete together, so the varying chloride diffusion coefficient in the matrix concrete is affected by the matrix concrete performances and concrete proportions. Normally, a higher concrete performance will bring out a lower chloride diffusion coefficient [18]. Furthermore, in the experimental results, the trends of increasing chloride diffusion coefficient in the correlation of crack depth are similar when the water-cement ratios are varied. It can be concluded that the trend of increasing the penetration depth and diffusion coefficient of chloride, when the crack depth varies, is independent on the proportion of concrete (W/C). From the linear regression of experimental results, an equation describing the influence of crack depth (L) on the chloride diffusion coefficient at crack zone of reinforced concrete is presented as follows:

\[ D_{\text{un-eff}} = 0.58L \ast 10^{-12} + D_{\text{uncr}} \]  \hspace{1cm} (10)

where \( L \) is crack depth (mm).

![Figure 7. The influence of crack depth on the chloride diffusion coefficient by STDT](image)

**Validation of Proposed Model**

The equation (5) describes the effective chloride diffusion coefficient (\( D_{\text{eff}}^{\text{cr}} \)). In the calculation of chloride profile, the effects of chloride binding capacity and the hydration time on the chloride diffusion have to be included in equation (5) to become the apparent chloride diffusion coefficient (\( D_{\text{app}}^{\text{cr}} \)) as follows:

\[ D_{\text{app}}^{\text{cr}} = D_{\text{eff}}^{\text{cr}} \ast \left( \frac{28}{t} \right)^a \phi \]  \hspace{1cm} (11)

where \( t \) is the age of concrete (day); \( a \) is the experiment coefficient, 0.3 for OPC [2]; \( \phi \) is the chloride binding capacity of a cement [9].

\[ \phi = (1 + \alpha) \]  \hspace{1cm} (12)

\[ \alpha = 0.56 + 0.025C_A \]  \hspace{1cm} (13)
$C_3A$ is a hydration compound of the cement.

By applying the Fick’s Second Law, equation (2) and the chloride diffusion coefficient at a crack zone of reinforced concrete, equation (4), the chloride profile at crack zone is calculated. Subsequently, the comparisons between the predicted and experimental results in the varying immersion periods are shown in Figure 8 to Figure 20.

![Figure 8. Comparison between predicted and experimental results (W/C = 0.4)](image)

![Figure 9. Comparison between predicted and experimental results (W/C = 0.5)](image)
Figure 10. Comparison between predicted and experimental results (W/C = 0.6)

Figure 11. Comparison between predicted and experimental results (W/C = 0.5)

Figure 12. Comparison between predicted and experimental results (W/C = 0.6)

Figure 13. Comparison between predicted and experimental results (W/C = 0.4)
Figure 14. Comparison between predicted and experimental results (W/C = 0.5)

Figure 15. Comparison between predicted and experimental results (W/C = 0.6)

Figure 16. Comparison between predicted and experimental results (W/C = 0.4)
Figure 17. Comparison between predicted and experimental results (W/C = 0.5)

8-week immersion, L = 31.5 mm

Figure 18. Comparison between predicted and experimental results (W/C = 0.6)

8-week immersion, L = 40.5 mm

Figure 19. Comparison between predicted and experimental results (W/C = 0.5; Crack 1)

16-week immersion, L = 45.5 mm
The proposed model used the surface chloride concentration in crack zone and average chloride diffusion coefficient ($D_{av}$) to predict the chloride profile at the locations of crack zones. The predicted results fitted very well with the experimental results, except for the samples immersed in salt solution during the initial weeks (2 weeks). In this case, an explanation is provided that the experimental results for chloride penetration are governed by the mechanism of movement of bulk chloride solution due to capillary suction. This capillary suction is assumed to primarily control the chloride transport through the whole crack at the initial ages of immersion periods. Then, the mechanism of chloride diffusion would be taken as following Fick’s second law. Inversely, the predicted results are obtained by the derivation of Fick’s second Law equation, which is applied for only diffusion mechanism. However, in case of immersion periods larger than 4 weeks, only the diffusion mechanism still controls the chloride penetration into concrete. That is why there is a good agreement between the experimental results and predicted ones.

Conclusions

- The research proposed a simple approach to predicting chloride profile in crack zone of reinforced concrete. The results of numerical calculation fit well with the experimental results. This developed model will become an important solution to evaluate the remaining service life of concrete structure when cracks appeared.
- Effects of crack characteristics, such as crack width and crack depth, were investigated on the chloride profile and chloride diffusion coefficient at the cracks of reinforced concrete structure. In addition to the crack width, the crack depth should be taken into account as an influence on chloride penetration into cracked reinforced concrete.
- The chloride penetration into cracked concrete increased as an increase of the crack depth and their rate trends were independent on the proportion of concrete, but dependent on the geometric of crack. The study also indicated that the service load had a significant role in increasing the chloride penetration due to a varying crack depth.
- The experimental results also showed the influence of the capillary suction mechanism on the chloride penetration into cracked concrete during the early periods of immersion by the movement of bulk chloride solution.

Figure 20. Comparison between predicted and experimental results (W/C =0.5; Crack 2)
Acknowledgments
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